CURRENT AND RECENT MOVEMENT ON THE SAN ANDREAS FAULT

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PART 1. HORIZONTAL MOVEMENT

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A general program for the study of horizontal crustal movement in California was started by the U.S. Coast and Geodetic Survey about 1930. The areas selected for these studies were based on the recommendations of geologists, seismologists, engineers, and geodesists.

After the San Francisco earthquake of 1906, the primary network of triangulation in the area, originally observed in 1880–1885, was reobserved to determine the extent of horizontal movement. The network was reobserved again in 1922. Results obtained from these repeat surveys disclosed conclusively that relative movement between points could be detected in areas of seismic activity.

The survey networks observed for the study of horizontal movement were established at various places along the major faults. These networks have been reobserved at periodic intervals, and horizontal movement is disclosed by changes in the final coordinates at each station in the net. The results which indicate movements are always given in relative terms. On opposite sides of a fault, the relative movement between points may be either right or left lateral. Right-lateral movement is indicated when the azimuth between two points is increased, or the line joining the points rotates in a clockwise direction. When the azimuth is decreased, relative movement between the points is left lateral or counterclockwise.

In each area along the San Andreas fault where the surveys have indicated movement, the direction of movement has been right lateral. That is, the west side of the fault has moved northwest relative to the east side, or the east side has moved southeast relative to the west side. Table 1 shows the dates of survey and indicated annual rate of movement at various localities from Point Reyes to El Centro. A summary of the results at each numbered locality is given in the correspondingly numbered paragraphs that follow.

Table 1. Annual rate of movement along San Andreas fault at localities discussed in text.

Locality	Position		Dates of survey	Annual rate of movement (cm)
	Lat.	Long.		
1	38.1°	122.8°	1930–38–60	1.3
2	37.6	122.0	1951–57–63	2.5
3	36.8	121.5	1930–51–62	1.6
4	36.7	121.4	1957–59–60–61–62–63–65	1.5
5	36.4	120.9	1944–63	3.0
6	35.7	120.3	1932–51–62	0.3
7a	35.0	119.4	1938–49–59	0
7b	34.8	118.8	1938–49	0
7c	34.5	118.1	1938–47–58	0
7d	34.3	117.5	1949–63	0
8	32.8	115.5	1935–41–54	3.0*

* Annual rate from 1941 to 1954.

(1). Point Reyes to Petaluma

This network starting at Point Reyes on the coast extends northeastward across the San Andreas fault to Petaluma. The net was established in 1930 and was reobserved in 1938 and again in 1960. Results of these surveys indicate that relative movement between points near and on opposite sides of the fault was on the order of 2 cm per year for the period from 1930 to 1938. During the interval from 1938 to 1960 the annual rate of movement was about 1 cm.

(2). Vicinity of Hayward

Surveys for the study of horizontal movement were established in this area in 1951. This network of triangles, with sides 9 to 12 km in length, straddles the Calaveras and Hayward faults, and the San Andreas fault extends along the western side of the area. Horizontal movement between surveys of 1951 and 1963 is indicated by vectors in figure 1. These results are based on least-square adjustments using the same control for each set of observations. The geographic position of station 18 was held fixed in the adjustment and also the azimuth and length of the line to station 17. Adjusted results of the 1957 survey are in very close agreement with results obtained from the 1963 observations. There is no indication of any significant movement during this 6-year period.

The quadrilateral involving stations 17, 18, 19, and 20 was first observed in 1882, and observations were repeated in 1906, 1922, and 1947. Results from these observations showed that station 19 moved northwesterly about 5 cm per year during the period 1882–1947. During this same 65-year period, station 20 moved southeasterly about 2 cm per year (Whitten, 1949).

Results of the 1951 and 1963 surveys show that stations 19 and 20 moved northwesterly about the same amount, 6 cm per year, during this 12-year pe-

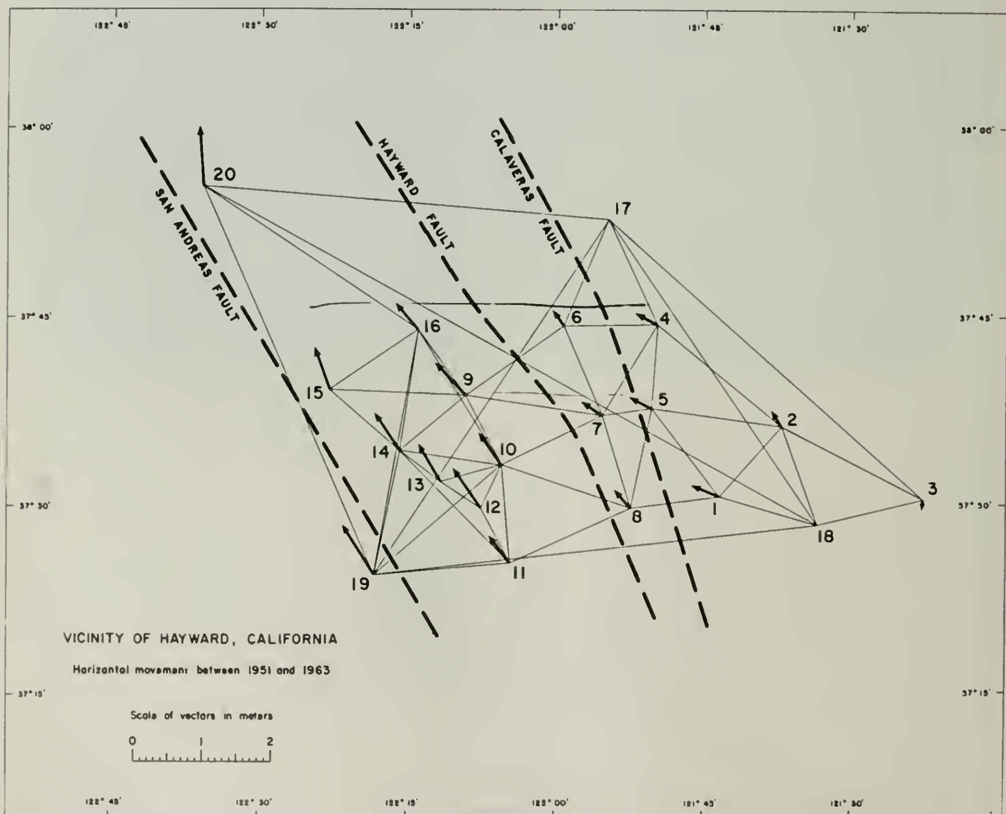

Figure 1. Triangulation network extending from Mount Tamalpais to Mount Oso, showing amount of horizontal movement between 1951 and 1963.

riod. The movement indicated at stations 19 and 20 is relative to the control stations 17–18, and part of this movement could be due to a change in the orientation of the figure. Final data for each survey are based on the assumption that the azimuth of the control line did not change.

The magnitude of the vectors at points near and on opposite sides of the Hayward fault indicates relative movement of about 0.3 m for the 12-year period or an annual rate of 2.5 cm. The change in the direction of the vectors indicates a possibility of compression in this area.

For future studies of horizontal movement, the Coast and Geodetic Survey has made tentative plans to establish two small nets straddling the Hayward fault in this area. The sides of these figures will be 200 to 400 m in length. Three nets of this type, two straddling the Hayward fault and one the Calaveras fault, were established in this area in 1965. Surveys involving these nets are described under a cooperative project with the California Department of Water Resources.

(3). Vicinity of Monterey Bay

This net extends from the coast at Monterey Bay northeastward through Salinas and crosses the San Andreas fault near Hollister. Observations were first made in 1930 and repeat observations were made in 1951 and 1962. Results of the surveys show the same rate of movement during the two intervals, 1930–1951 and 1951–1962. During each of these periods, the annual rate of movement was 1.6 cm between points on opposite sides of the fault.

(4). Vicinity of Hollister

A quadrilateral straddling the San Andreas fault, with sides approximately 300 m in length, was established near a winery south of Hollister in 1957. The quadrilateral was reobserved in 1959, 1960, 1961, 1962, and 1963. Relative movement, divided equally between points on opposite sides of the fault, is shown by vectors in figure 2. This relative movement, averaging 1.5 cm per year, is based on the difference between surveys of 1957 and 1963. However, the difference between consecutive surveys indicates the movement is fairly uniform and on the order of 1.5 cm per year. The two sides parallel to the fault have not shown any significant change in direction or length. Sides 5–6 and 7–8, perpendicular to the fault, have increased in azimuth an average of 11 seconds per year. The diagonal 6–8 increased 7.7 cm in length, and the other diagonal decreased 5.9 cm during the 6-year period 1957–1963.

A resurvey of this figure was completed in June 1965. During the 20-month interval from October 1963 to June 1965, results showed relative movement of 1.7 cm between points on opposite sides of the fault.

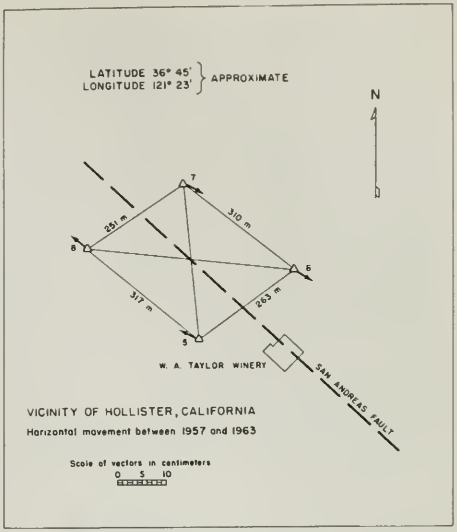

Figure 2. Quadrilateral near winery south of Hollister, showing cumulative horizontal movement between 1957 and 1963.

The annual rate of movement determined from these surveys is in close agreement with the rate obtained from creep recorders installed near the winery in 1957 and 1958 (Tocher, 1960).

(5). Salinas River Valley

This triangulation network extending along the San Andreas fault from the 36th parallel northwesterly for a distance of approximately 100 km was observed in 1944 as an extension of the national horizontal control net. An extension of this net in 1962 indicated that movement had taken place between points on opposite sides of the fault. In order to determine the extent of movement in the area, the 1944 network was reobserved in 1963.

Differences between the adjusted results of the 1944 and 1963 observations are indicated by vectors in figure 3. The movement indicated is relative to the fixed control station, number 11. For all stations on the western side of the fault, observations made in 1963 were in very close agreement with those of 1944. Differences between the adjusted lengths and azimuths of 9 lines crossing the fault are given below. Numbers identifying the lines are shown in figure 3.

The maximum changes in length are on lines crossing and in the general direction of the fault, as indicated under (a). Maximum changes in azimuth are on

Table 2.

Line	Length meters	1963 minus 1944	
		Length meters	Azimuth
(a) 3–9	17,059	−0.50	− 1.9″
9–15	13,114	+0.69	+ 0.9
14–23	36,415	+0.71	+ 1.0
(b) 12–15	15,651	+0.27	+ 8.2
17–15	14,179	−0.09	+ 8.5
21–23	13,109	+0.04	+ 8.5
25–24	14,957	+0.20	+ 9.6
25–22	5,882	+0.21	+21.2
28–29	14,739	+0.23	+ 7.8

lines approximately perpendicular to and crossing the fault. When the lengths are used to convert azimuth changes to displacement, the following values are obtained for lines under (b).

Table 3.

Line	Displacement meters
12–15	+0.62
17–15	+0.58
21–23	+0.54
25–24	+0.70
25–22	+0.60
28–29	+0.56
average	+0.60

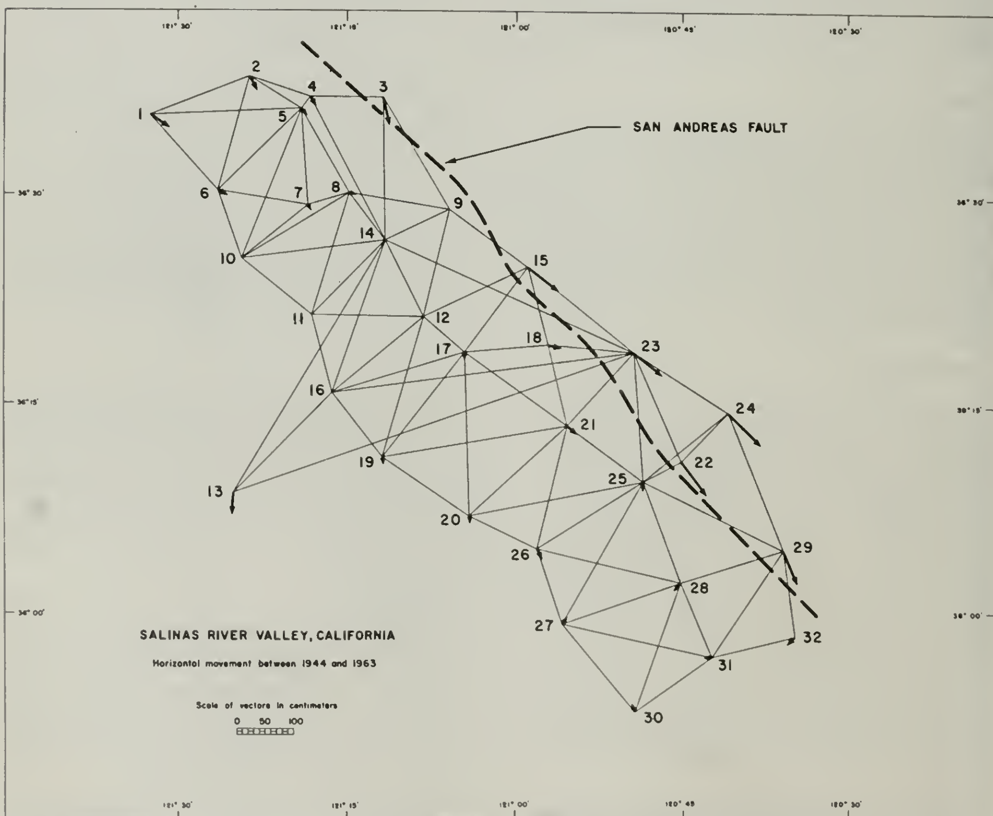

Figure 3. Triangulation network extending from a few miles southeast of Salinas to a point several miles northwest of Parkfield, showing horizontal movement between 1944 and 1963.

The average value for this displacement is in close agreement with the length changes under (a), lines in the direction of and on opposite sides of the fault.

The relative movement determined from results of the 1944 and 1963 surveys is fairly uniform along the San Andreas fault in this area. Between points on opposite sides of the fault the average relative movement was 3 cm per year (Meade, 1965).

(6). San Luis Obispo to Avenal

This triangulation net, about 100 km in length, crosses the San Andreas fault in the vicinity of Cholame. The original survey was accomplished in 1932 and reobservations were made in 1951 and 1962. For stations near the fault, the relative movement was 5 cm for the 20-year interval 1932–1951. During the period from 1951 to 1962, the relative movement was about the same as that for 1932–1951.

(7). The 35th Parallel to Cajon Pass

Along the San Andreas fault from the 35th parallel to Cajon Pass, repeat surveys for the study of crustal movements have been made in the vicinities of (a) Maricopa, (b) Gorman, (c) Palmdale, and (d) Cajon Pass. The various surveys in these areas have not disclosed any significant movement.

(8). Imperial Valley, Vicinity of El Centro

The San Andreas fault crosses the middle of this area which is adjacent to the Mexican border. The original survey was made in 1935 and resurveys were made in 1941 and 1954. Large relative movements between points on opposite sides of the fault were disclosed from results of the 1935 and 1941 surveys. These changes occurred at the time of the severe earthquake in the area in 1940. The annual rate of movement between points on opposite sides of the fault was 3 cm during the period 1941–1954 (Meade, 1963).

Taft-Mojave Area

An extensive triangulation net was established in 1959–60 over the area where the San Andreas, Garlock, White Wolf, and other faults converge. Previous surveys along the San Andreas fault in this area have not disclosed significant movements. Along the 35th parallel from Wheeler Ridge to the east, surveys of 1932, 1952, and 1963 indicate a possibility of left-lateral movement along the Garlock fault.

A resurvey of this extensive network will furnish valuable information on crustal movements along the various faults in this area.

Cooperative Project With Department of Water Resources

In cooperation with the California Department of Water Resources, surveys for the study of crustal movements were started in 1964 in areas where a proposed aqueduct and its branches parallel or cross known fault lines. The figures established at these crossings range in size from 150 by 260 m to 500 by 900 m. A typical net of this type is shown in figure 4.

Seventeen aqueduct-fault crossings of the type shown in figure 4 were established and observed in 1964. A precise base line was measured and an astronomic azimuth was observed in each net. These nets are located at various intervals along the major faults of southern California extending from approximate position 34.1° N., 117.3° W. to 35.7° N., 120.2° W. A complete resurvey of each of the 17 nets was completed during the spring of 1965. Results of the surveys did not show conclusively that horizontal movement had taken place.

Four additional nets of the type mentioned above were established in the San Francisco Bay area in 1965. Also another net at the site of the proposed Cedar Springs Reservoir about 15 miles north of San Bernardino was added to the project early in 1965. It was surveyed in February 1965 and again at the end of the season's work in May 1965. No movement between surveys was apparent. Tentative plans have been made to resurvey each of the 22 nets straddling the faults at intervals of 1 or 2 years.

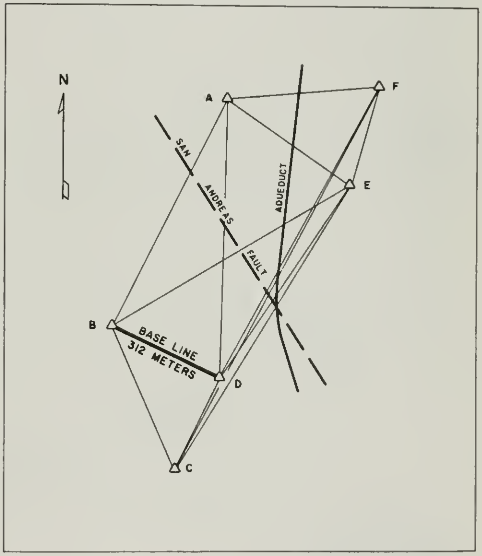

Figure 4. A typical triangulation net about proposed aqueduct-fault crossing.

Along the San Andreas fault from the vicinity of Point Reyes to the 36th parallel, repeat surveys for the study of crustal movement continue to show right-lateral movement. From the vicinity of the 36th parallel to Cajon Pass these surveys have not disclosed any significant movement along the fault. In the Imperial Valley the relative movement is in the same direction and about the same magnitude as that along the fault from Hayward to the 36th parallel.

PART 2. VERTICAL MOVEMENT

By J. B. Smoll
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The Coast and Geodetic Survey is responsible for the basic vertical control net of the United States. The first leveling undertaken in California in the development of this net was in 1906. About 30,000 miles of first-order leveling and 20,000 miles of second-order leveling have been undertaken in California, including the original leveling and releveling to determine vertical changes. California is considered one of the most difficult areas in which to undertake leveling because of the many factors contributing to change, some of which are: removal of underground water, oil, and gas; changing moisture content of the soil; fault lines; earthquakes; tectonic and secular changes. To determine the magnitude of change in an absolute sense, the releveling needs to be extended to what are considered stable areas or to coastal locations where mean sea level has been determined through tide gauge records. Often it is difficult to determine what areas to consider stable, since even the survey markers established in bedrock to serve as anchors are subject to some small slow changes.

The most concentrated releveling has been in cooperation with the California Department of Water Resources in the San Joaquin Valley. Areas of most rapid subsidence have been where there is a removal of underground water, oil, or gas. In the San Joaquin Valley, the maximum subsidence was 22.890 feet from 1943 to 1964 at a location about 10 miles southwest of Mendota. Another cone of subsidence in the San Joaquin Valley is located in the Delano area. The maximum subsidence was 11.437 feet from 1930 to 1964 at a location 2 miles north of Earlimart. In the vicinity of San Jose, at the southern end of San Francisco Bay, the maximum subsidence from 1912 to 1963 has been 11.2 feet. There has been an accelerated rate of subsidence from 1960 to 1963 with a maximum during this period of 1.94 feet. Usually the vertical changes are considered to be subsidence; however, there are some areas where relevelings indicate some small upheaval. One aspect of particular interest in this study is the movement of marks in bedrock. About 5 miles southeast of San Jose and west of the Hayward fault line, there is a group of bench marks in bedrock which is classed as ultrabasic. These marks are relatively stable and have been used as tie marks between the various levelings because they agree best when checking with tidal bench marks at San Francisco. There is another group of bedrock marks in Alum Rock Park which is about 7 miles northeast of San Jose on the east side of the Hayward fault trace. Between 1948 and 1963, the bedrock marks in Alum Rock Park raised about 0.213 foot in relation to those southeast of San Jose. The various relevelings have shown this to be a gradual rise. The length of the leveling connecting these two groups of marks is about 12 miles. In the vicinity of Lebec, near the San Andreas fault, releveling in 1964 carried from San Pedro indicates an upheaval of 0.55 foot, and releveling of 1965 indicates an upheaval of 0.82 foot.

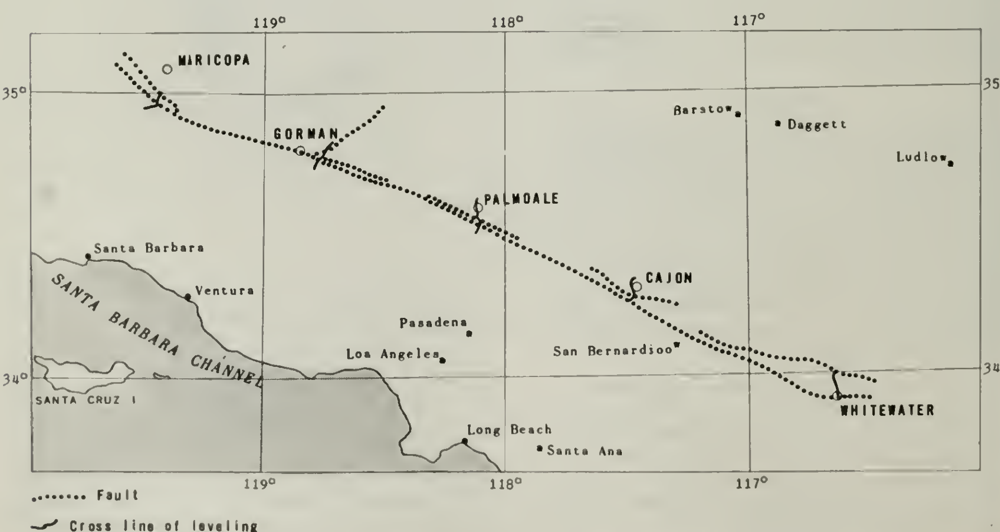

Figure 5. Locations of special levelings established in 1935 across San Andreas fault between Maricopa and Whitewater.

In 1935, five lines of leveling were established at right angles to the San Andreas fault (see fig. 5). The level lines were about 10 miles in length with about 200 bench marks on each line. The marks were established approximately 100 feet apart for the first mile each way from the fault line, 200 feet apart for the second mile, 300 feet for the third mile, 400 feet for the fourth mile, and 500 feet for the fifth mile.

The locations at which these lines were established and the dates of the leveling are as follows:

Table 4.

Line no.	Location	Dates of leveling
1.	Vicinity of Whitewater	1935, 1949. (2 levelings).
2.	Vicinity of Cajon Pass	1935, 1943–4 (Part), 1956, 1961. (4 levelings).
3.	Vicinity of Palmdale	1935, 1938, 1947, 1955, 1960 (Part), 1961, 1964, 1965. (8 levelings).
4.	Vicinity of Gorman	1935, 1938, 1953, 1961, 1964. (5 levelings).
5.	Vicinity of Maricopa	1935, 1938, 1948 (Part), 1953, 1956, 1959, 1964. (7 levelings).

The maximum and average divergence between levelings for the above lines are as follows:

Table 5.

Line no.	Maximum divergence between levelings	Average divergence
1.	0.174 meter or 0.571 foot	0.01 meter or 0.03 foot
2.	0.071 meter or 0.233 foot	0.04 meter or 0.13 foot
3.	0.363 meter or 1.191 feet	0.07 meter or 0.23 foot
4.	0.066 meter or 0.217 foot	0.04 meter or 0.13 foot
5.	0.439 meter or 1.440 feet	0.03 meter or 0.10 foot

In 1964, small groups of marks were set at 22 locations stradling the San Andreas and other major faults. In 1965, releveling was undertaken at 15 of these locations.

The maximum vertical relative changes are as follows:

Table 6.

Site no.	Location	Latitude	Longitude	Vertical change 1964 to 1965 (mm)
1	Colt	34.1°	117.3°	2.6
2	Rialto	34.1	117.3	5.7
3	Devil	34.2	117.3	8.2
4	Cedar	34.3	117.3	5.0
5	Wright	34.4	117.7	7.2
6	Pear	34.5	117.9	4.8
7	Barrel	34.5	118.1	10.1
8	Palm	34.6	118.2	12.7
9	Hughes	34.7	118.5	7.8
10	Warm	34.6	118.5	26.4
11	Cast	34.5	118.6	11.4
12	Quail	34.8	118.8	4.4
13	Ranch	34.9	118.8	22.4
14	Tejon	34.9	118.8	11.8
15	Mettler	35.0	119.0	8.1

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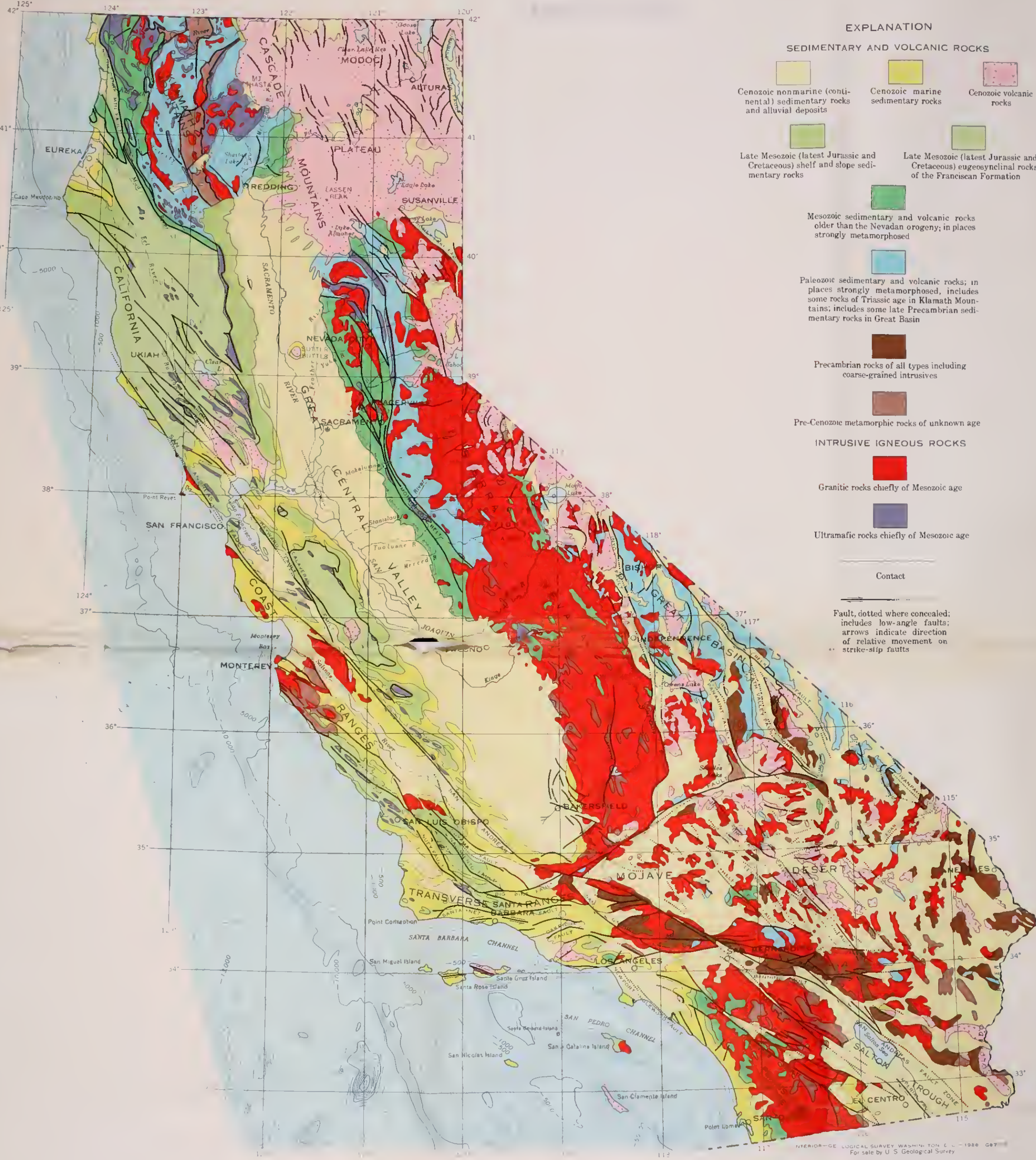
DEPARTMENT OF INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

- Cenozoic nonmarine (continental) sedimentary rocks and alluvial deposits
- Cenozoic marine sedimentary rocks
- Cenozoic volcanic rocks
- Late Mesozoic (latest Jurassic and Cretaceous) shelf and slope sedimentary rocks
- Late Mesozoic (latest Jurassic and Cretaceous) eugeosynclinal rocks of the Franciscan Formation
- Mesozoic sedimentary and volcanic rocks older than the Nevadan orogeny; in places strongly metamorphosed
- Paleozoic sedimentary and volcanic rocks; in places strongly metamorphosed, includes some rocks of Triassic age in Klamath Mountains; includes some late Precambrian sedimentary rocks in Great Basin
- Precambrian rocks of all types including coarse-grained intrusives
- Pre-Cenozoic metamorphic rocks of unknown age

INTRUSIVE IGNEOUS ROCKS

- Granitic rocks chiefly of Mesozoic age
- Ultramafic rocks chiefly of Mesozoic age

Contact

Fault, dotted where concealed; includes low-angle faults; arrows indicate direction of relative movement on strike-slip faults

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1966
For sale by U. S. Geological Survey

GEOLOGIC MAP OF CALIFORNIA

COMPILED BY U.S. GEOLOGICAL SURVEY
AND CALIFORNIA DIVISION OF MINES AND GEOLOGY

SCALE 1:2 500 000

0 50 100 MILES

SUBMARINE CONTOUR INTERVALS 500 AND 1000 FEET. DATUM IS SEA LEVEL

1966